Joint Milli-Arcsecond Pathfinder Survey (J-MAPS) Mission: The Application of High Metric Accuracy Astrometry to Space Situational Awareness

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ABSTRACT

Two critical aspects of the Space Situational Awareness (SSA) problem are detection and orbit generation for Resident Space Objects (RSOs). The two problems have two different instrumentation solutions. Existing and planned ground and space-based optical systems are optimized for detection, with the result that their ability to measure the position and velocity of RSOs of interest is compromised. An SSA architecture would potentially benefit from supplementing existing and planned detection assets with a dedicated high-accuracy orbit determination system or systems, with the potential for 24/7 taskability and near-real time capability. By optimizing an instrument to perform position measurement rather than detection, significant (i.e., one or more orders of magnitude) improvement may be realized in position and velocity measurement (thus, orbit determination) vs. other current and envisioned systems.

The United States Naval Observatory (USNO) is developing the space-based J-MAPS mission to support current and future star catalog and star tracker requirements. By its very nature, USNO's J-MAPS mission, a microsatellite designed to take very high precision measurements of star positions (astrometry), is ideally suited to make these high metric accuracy measurements for brighter GEO RSOs.

Background material is presented on the current state of astrometric measurements from ground and space, and we will motivate the need to apply high metric accuracy astrometry to the SSA problem. As a solution, we will discuss capabilities of the J-MAPS mission. To support SSA, J-MAPS would demonstrate the ability to measure geosynchronous satellite positions to absolute accuracies of better than 10 m (plane-of-the-sky), the ability to autonomously range with accuracies of order 100 meters over a few tens of minutes of observing time, and the ability to monitor regions around specific assets and detect and observe delta-V maneuvers.

1.0 INTRODUCTION

Astrometry is the subfield of astronomy concerned with the measurement of the positions of celestial bodies along with their real and apparent motions. The principle astrometric measurables are position (2 coordinates), proper motion (2 coordinates), and parallax. Stellar position is measured in the celestial coordinates of right ascension and declination, in a reference frame consistent with the internationally adopted International

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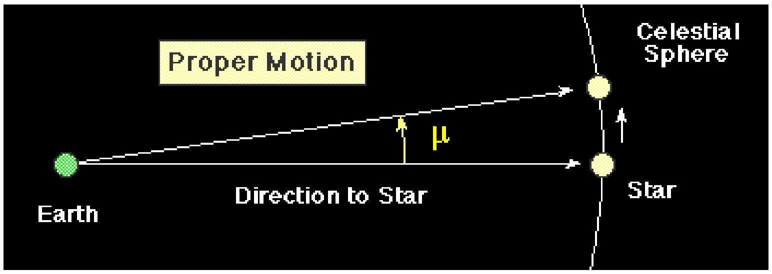
Celestial Reference System (ICRS). The proper motion of a star is related to its Newtonian motion through space. Parallax is the annular motion of a star directly related to its distance from the Earth (see Figure 1).



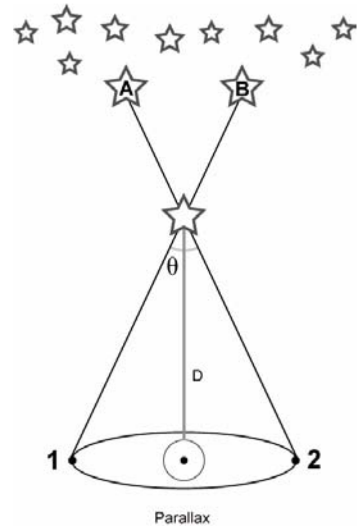


Figure 1: (Left) the proper motion of a star is related to its individual velocity through space. (Right) the parallax of a star is an apparent cyclical motion (period 1 year) observed against stars and other celestial objects at much greater distance. Parallax is attributed to the Earth's orbital motion around the Sun. Periods of maximum parallax occur at intervals of six month (labelled 1 and 2 in the Figure) and is related to the star's distance from Earth. Nearby stars exhibit the largest parallaxes.

The era of high metric accuracy astrometry began in the last decade with the successful completion of the Hipparcos mission (Figure 2). The world's first (and up to this point only) space astrometry mission, Hipparcos, sponsored by the European Space Agency, produced a star catalog of 120,000 stars with nominal accuracy to approximately 1 milliarcsecond (mas) at 9th magnitude (note: 1 mas equals 4.8 nanoradian) referenced to a 1991 epoch. Hipparcos observed all stars in the sky brighter than 7th magnitude and selected stars between 7th and 12th magnitudes. Proper motion measurement uncertainties were 1 mas/year for the resulting Hipparcos catalog, so positional knowledge of individual stars in the Hipparcos catalog has degraded to approximately 15 mas in 2006.

Figure 2: Notional view of the European Space Agency Hipparcos astrometric satellite. Hipparcos was launched in August 1989 and operated until August 1993.

2.0 NATIONAL SECURITY USE OF ASTROMETRIC STAR CATALOGS

We discuss two principal national security uses for astrometric star catalogs: a) determination of space platform orientation and b) Space Situational Awareness (SSA), specifically focussed upon rapid, precise determination of Resident Space Object (RSO) position and motion. As discussed in Section 3, the J-MAPS mission will make important contributions in both of these areas.

2.1 Determination of Space Platform Orientation for Precise Geolocation

The process of geolocation refers to the assignment of terrestrial coordinates to a particular data collection observed by a downlooking imaging sensor. Geolocation error is the position error of the data collection, typically expressed in terms of meters. In this section we restrict our consideration to *autonomous geolocation*, that is, determination of location without reference to external features or known landmarks. Autonomous geolocation is necessary when considering data collections without ground control points; i.e., with transient or shifting features, including ocean, coastline, and desert terrain. This is especially important in today's world, where there is often a desire to obtain precise terrestrial coordinate data for mobile and highly distributed assets, perhaps in terrain with few landmarks, making rapid geolocation determination for a particular data collection a very difficult process.

To meet geolocation goals and minimize geolocation errors, space platforms must have adequate knowledge of both their position above the Earth and their orientation with respect to the Earth. There are a variety of different ways to obtain satellite position data, but high accuracy space platform orientation can only be derived through the use of star trackers. Many factors contribute to geolocation error including: errors in platform location, errors in Earth surface modeling, errors in Earth orientation parameters, and errors in asset orientation. Under certain circumstances, e.g., cases where data geolocation is difficult or impossible (see above), the latter source of error (orientation) can become the dominant component in the geolocation error calculation. Such conditions can occur even when technical means have been applied to reduce other sources of error. Orientation errors can also be exacerbated under certain geometric conditions (e.g., high altitude orbits) that are naturally more sensitive to orientation error.

Most current star trackers applications employ star catalogs and positions based on the Hipparcos catalog. Given the temporal degradation of the Hipparcos catalog, and the anticipation of tighter space platform orientation goals to meet future precise geolocation needs (see Figure 3), the U.S. National Space Security Office has included the following language in their 2007 report to the U.S. Department of Defense: *"(U) In order to meet future precision attitude, pointing, and navigation national security space needs, it is our recommendation that DoD take the lead in developing a ten milliarcsecond star tracker and in generating one milliarcsecond star position catalogs to support next generation star trackers."* As discussed in Section 3, the J-MAPS mission will not only provide a one milliarcsecond star catalog to meet the needs of the next generation of star trackers, but J-MAPS will also play a technology pathfinding role for the next generation of high accuracy star trackers.

2.2 Orbit Determination of Resident Space Objects

Two critical aspects of the Space Situational Awareness (SSA) problem are detection and orbit generation for Resident Space Objects. The two problems have two different instrumentation solutions. Existing and planned ground and space-based optical systems are optimized for detection, with the result that their ability to measure the position and velocity of RSOs of interest is compromised. In this section we discuss the potential benefit of supplementing the existing SSA architecture with one or more assets dedicated to high metric accuracy orbital determination with near-real time capability.

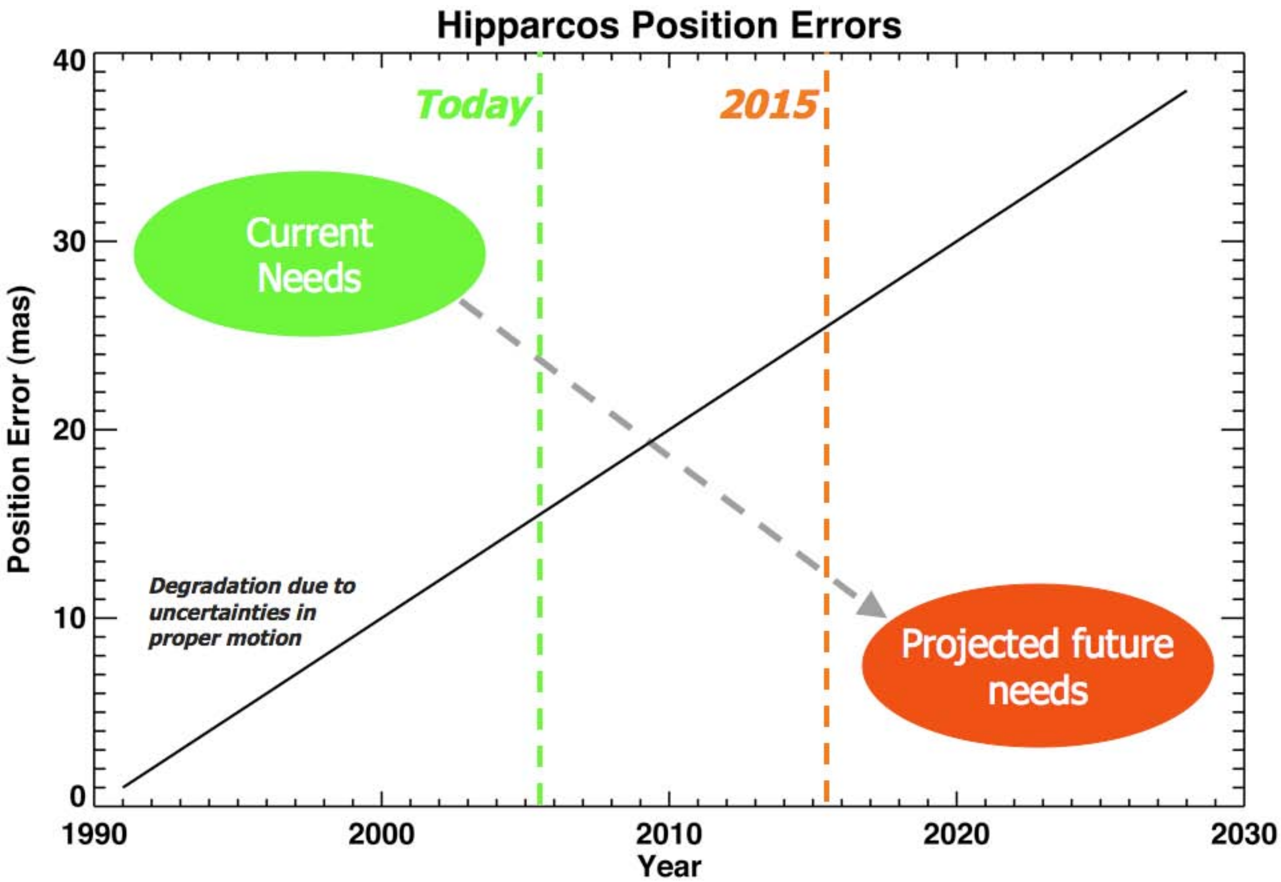


Figure 3. Degradation of the astrometric positional precision of the Hipparcos catalog as a function of time. The degradation of the Hipparcos catalog is approaching the region of current needs, and will not meet future needs for high accuracy star positions.

Space Situational Awareness (SSA)—the ability to understand where space assets are and what they are doing—is founded on two capabilities: *detection* and determination of the *position and velocity* of RSOs of interest. First, the RSO must be detected against the space background. Once detected, the RSO's position and velocity need to be determined and an orbit calculated. An RSO with a solved orbit can be periodically revisited and its orbit updated. For potentially hostile RSOs, maneuvers can be detected and threat potential can be assessed if the RSO's position and velocity is observed with sufficient accuracy. For high value systems, "keep out" regions around the asset can be monitored, and satellite operators can be notified when potentially hostile RSOs are maneuvering onto dangerous trajectories with respect to high value systems. For both offensive and defensive purposes, the more accurate the position and velocity measurements (and hence, the orbit), the better the SSA.

Current and planned ground and space-based SSA systems require many observations to determine RSO position and velocity with high accuracy. This is because these assets are optimized for solving the detection problem, and detection and tracking are two different measurement tasks. The detection of RSOs against the space background requires maximizing P_D (probability of detection) while simultaneously minimizing the FAR (False Alarm Rate). For typical space systems, this is accomplished by sizing the optics and detector pixel dimensions such that the Airy disk for a point source is contained within a single pixel. Furthermore, the pixel instantaneous field of view (IFOV, or the angle subtended by a single pixel on the sky) is chosen to be large enough to eliminate smearing due to differential motion between the RSO and the background.

High accuracy orbit determination requires precise position measurement of the RSO against a high accuracy background reference grid. High precision position measurement requires first determining the centroid of the RSO's point source function (PSF); this relative position is then referenced to the relative positions of multiple reference stars measured in same image. The high precision relative position of the RSO can then be converted to a high accuracy absolute position if the reference star positions are known with high accuracy.

High precision centroid determination requires proper sampling of the RSO and reference star PSFs rather than the significant level of undersampling desirable for detection. Undersampling introduces significant systematic errors that severely limit the centroiding precision possible. Furthermore, while elimination of streaks by employing large IFOVs is clearly desirable for maximizing S/N, it significantly limits the amount of position and velocity information present in the scene. The detection and position measurements tasks are thus at cross-purposes, and an instrument optimized for the former will be sub-optimal for the latter (see Figure 4).

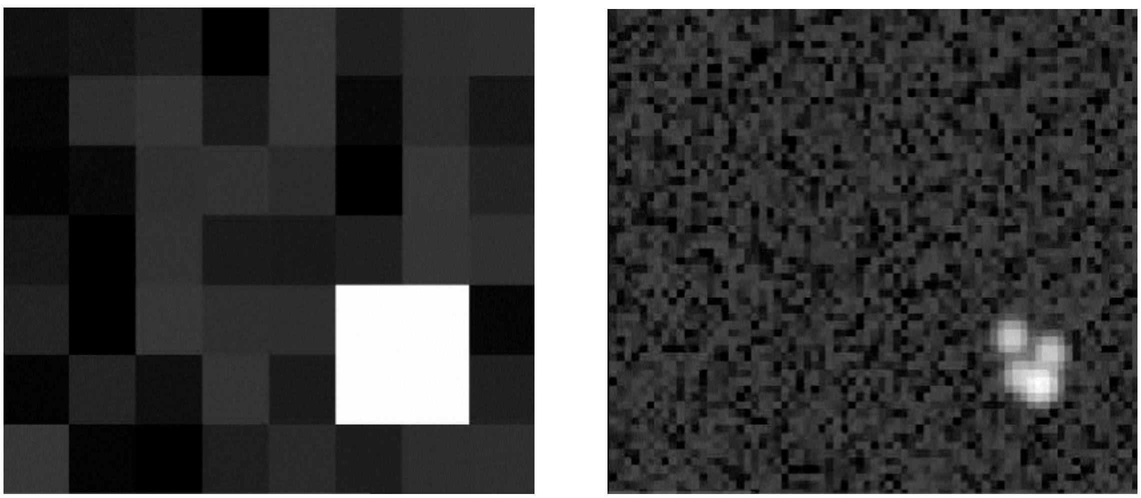


Figure 4. Simulated observation of a constellation of geosatellites as observed by (left) a typical (detection-optimized) space-based sensor, and (right) an astrometric (high metric accuracy-optimized) space-based sensor.

Future SSA needs will move into the regime of rapid, highly precise orbit determination. To support rapid threat analysis for satellites maneuvering in the vicinity of high value assets, and enable satellite operators the opportunity to take effective defensive counterspace actions when required, highly precise orbit determination will necessarily be required in near-real time. This motivates the SSA need for precise (~1 mas) background star catalogs, and high metric accuracy astrometric space surveillance sensors. In the next section we discuss USNO's proposed Joint Milli-Arcsecond Pathfinder Survey (J-MAPS) satellite—designed to perform very high accuracy measurements of star position, and J-MAPS' ability to conduct an on-orbit advanced concept demonstration of high metric accuracy SSA observations, with the potential for improving orbit determination accuracy by one or more orders of magnitude, and generating high-accuracy orbit solutions much more quickly than other current and envisioned SSA systems.

3.0 THE JOINT MILLI-ARCSECOND PATHFINDER SURVEY (J-MAPS)

To meet national security space needs, the U.S. National Security Space Office has recommended that the U.S. DoD take the lead in the development of a 10 mas star tracker along with a 1 mas star catalog to support the needs of this star tracker (see section 2.1). In the previous section (2.2) we discussed how highly precise, near-real time orbit determination will require high metric accuracy measurement of RSO positions against a high metric accuracy astrometric grid of background stars. The U.S. Naval Observatory has been developing the J-MAPS mission to meet these needs.

J-MAPS (Figure 5) is a microsatellite, deployed into Low Earth Orbit (LEO) with a two to three year required mission life. The primary instrument (Figure 6) is an optical telescope consisting of a 15-cm aperture and an 8k x 8k focal plane assembly (FPA). The instrument has a 1 degree by 1 degree FOV, with each pixel IFOV equal to approximately 500 mas (≈2.5 microrad). The instrument is designed to observe all stars through visible magnitude (m_V) 14 (req) and 16 (goal), with a reference mission accuracy of < 1 milliarcsecond (mas) at m_V=10. The mission will image each field repeatedly, with every star observed at least 25 times by the end of the mission. The current baseline for J-MAPS is a 900-km, sun synchronous orbit (SSO), oriented along the Earth's terminator. Funding discussions are currently underway with potential sponsors. Salient features of the J-MAPS microsatellite are listed below.

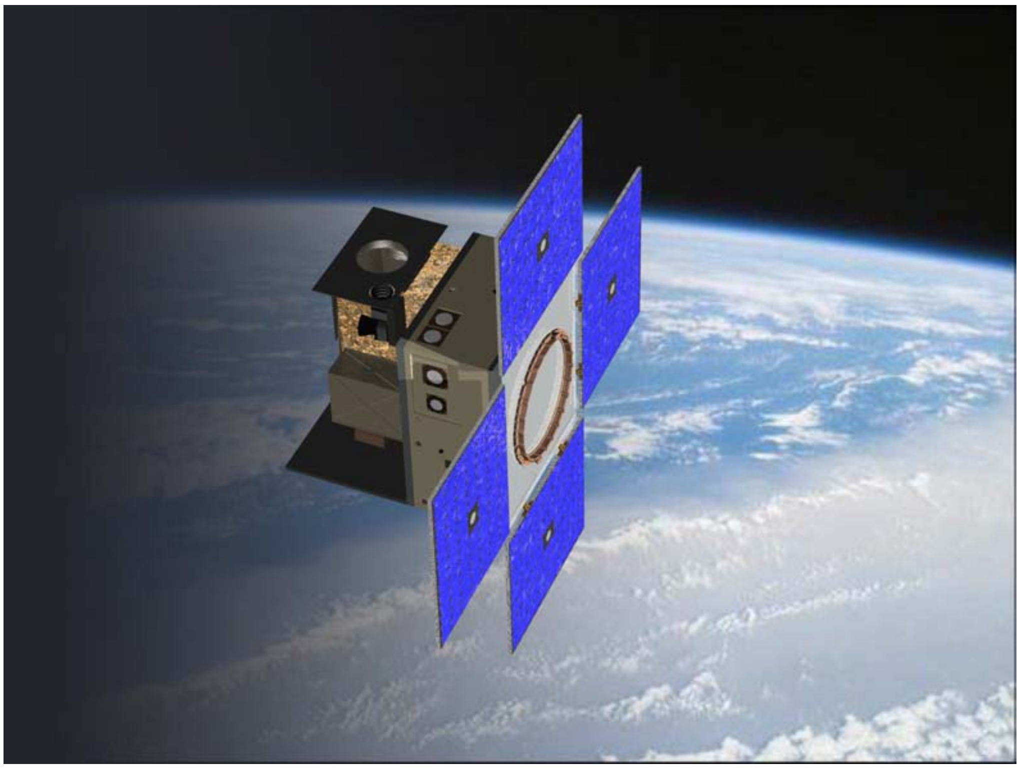


Figure 5. J-MAPS' baseline orbit is terminator, sun synchronous, and at an altitude of 900km

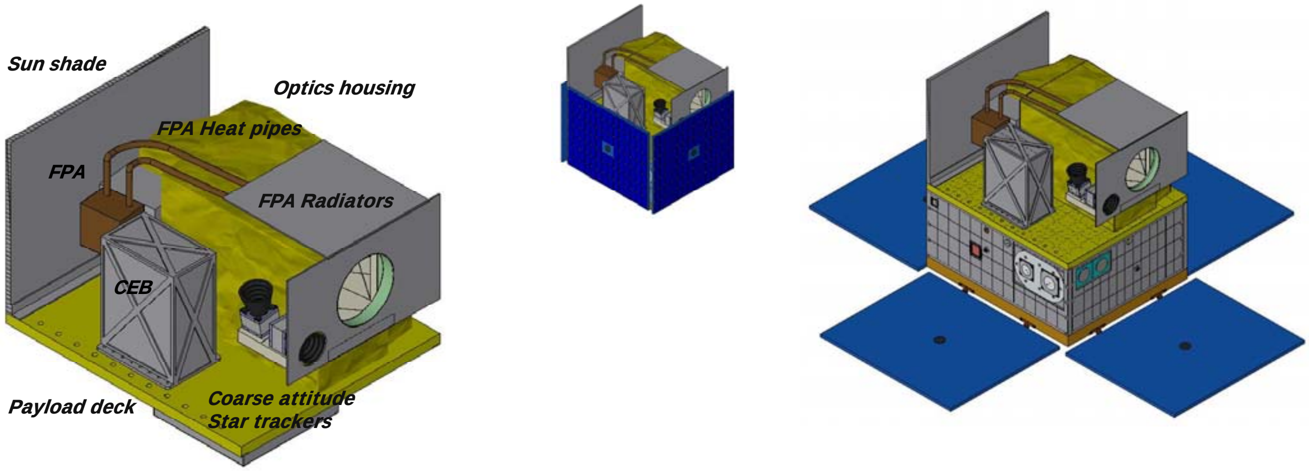


Figure 6. (Left) J-MAPS Payload Deck, (Middle) Stowed configuration, (Right) Deployed configuration

J-MAPS instrument:

- Telescope: 15 cm, off-axis FMA telescope
- Focal Plane:
  - 8k x 8k active pixel sensor (APS) detector
  - CMOS-Hybrid or similar technology
- Camera Electronics Box (CEB):
  - Clocks, biases, ADC, mass memory, data processing, FPA temp control
- Mass = 30 kg (w/margin)
- Power = 100 W (w/margin)
- < 100 mW dissipated on the FPA
- Temp. control
  - FPA = 193 ± 0.1 K
  - All else = ambient (≈273 K)
- Attitude determination
  - Coarse (15 arcsec): 2 x star trackers
  - Fine (<50 mas): primary instrument

Overall:

- Mass: 84 kg (bus), 115 kg (total)
- Power: 66 W (bus), 169 W (total)

3.1 J-MAPS High Metric Accuracy Plane-of-the-Sky Position Measurements

As described above, in order to generate high accuracy orbits for RSOs, one needs 1) a high-accuracy background stellar reference grid, 2) an instrument capable of making high metric precision observations of an RSO against the stellar references, and 3) very high accuracy knowledge of the observer's position. J-MAPS supports all of these requirements:

The J-MAPS-generated reference grid of <1 mas for all stars through 10th magnitude will not only be approximately 15 times more accurate than the current epoch's best optical reference system, the Hipparcos catalog, but also hundreds of times denser. A one mas reference grid accuracy is the equivalent of approximately 20 cm at GEO distance.

The J-MAPS instrument has been designed specifically to achieve very high centroiding precision for stellar sources. Unlike detection-optimized instruments, the PSFs will be properly sampled and designed to support 1/100th pixel or better centroiding precision for stars. The IFOV of a J-MAPS pixel will subtend approximately 85 m at GEO, while the overall FOV will cover a square approximately 700 km on a side at GEO. Assuming 1/10th to 1/20th of a pixel centroiding on streak endpoints, we estimate a measurement precision of 4—8 m at GEO. The SSO/Terminator orbit currently baselined for J-MAPS allows access to the GEO opposition region—where GEO satellites are brightest due to solar aspect angle considerations—at all times (see Figure 7).

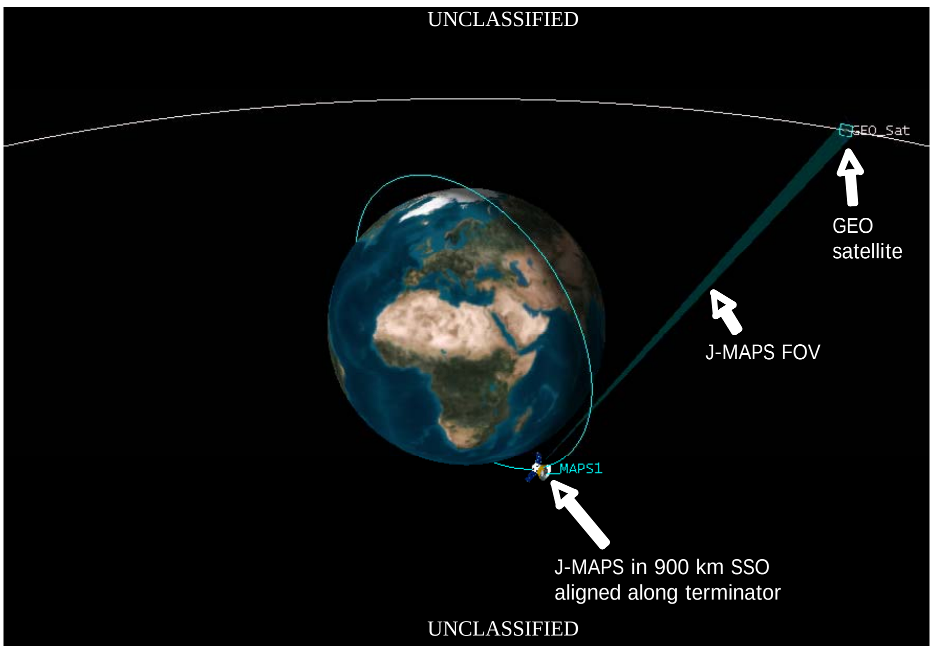


Figure 7. The baseline J-MAPS orbit is ideally suited for observing GEO satellites near oppostion

J-MAPS will include, on-board, next generation space GPS technology. We are currently in discussions with both NASA/Goddard Space Flight Center and USAF/SMC regarding the optimal GPS solution. Using this next generation GPS technology, we expect to be able to determine the J-MAPS' absolute position to 1 m or better to support SSA observations.

We envision two possible SSA demonstration modes:

Sidereal Mode

This is the standard operating mode for J-MAPS. The satellite maintains track on the background stars while the instrument takes exposures. Data images would look similar to Figure 8. The differential motion of J-MAPS and a GEO satellite will result in streaks of approximately ~30 pixels per second. This is the equivalent to 3—4 magnitudes of signal suppression. Given the relatively small optics subsystem employed by J-MAPS, streaking restricts suitable observations to relatively large GEO objects near opposition.

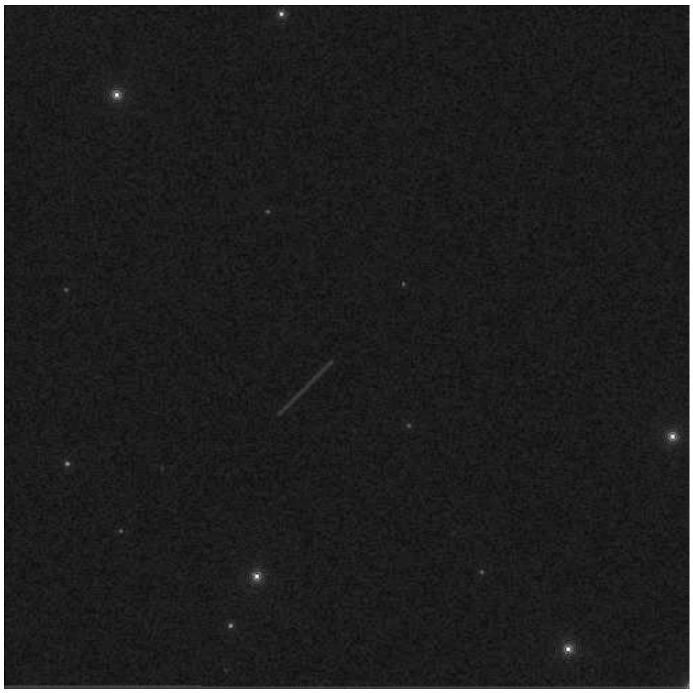


Figure 8. J-MAPS SSA Observation. RSO shown as a streak. RSO position is determined by measuring relative positions of streak endpoints with respect to reference stars of known positions.

Assuming a source brightness of 11-12th magnitude, we estimate streak endpoint position measurements of 25—50 mas (4—8 m at GEO) precision. For a ten second sequence of 1 sec exposures with two endpoints each, we estimate single epoch precisions of ~ 10 mas, or approximately 2 m at GEO, in plane-of-the-sky position. Folding in other sources of error (satellite position and timing errors), we estimate < 10 m plane-of-the-sky measurement accuracy at GEO is feasible with a source limiting magnitude of ~11-12^{m}.

Geo Mode

In this mode, J-MAPS would track at the GEO rate rather than the sidereal rate. RSOs at GEO would appear as point-sources while the background stars would streak. In GEO mode, the limiting magnitude for RSO observations would be ~15th magnitude rather than 11th magnitude due to the elimination of RSO streaking. We estimate RSO position measurement precision to be at the meter level. This mode is especially well suited to monitoring multiple RSO (constellations, for example) in the 700-km FOV box and measuring relative positions and motions such as small delta-V maneuvers (see Figure 4). Based on previous work done with the USNO Flagstaff 1.3m telescope, relative position and motion changes of order 1 m and 1 m/s should be detectable in this mode. Absolute positions would be calculated by referencing the endpoints of the streaking stars. Folding in other sources of error (e.g., satellite position and timing errors) we estimate position accuracies for this mode of order 20 m with an RSO limiting magnitude of 15^{th} magnitude.

By comparison, other current and envisioned systems measure at accuracies of hundreds of meters or more. In order to calculate orbits with high accuracy, these systems require observations over multiple orbits. By contrast, J-MAPS could be used to very quickly (tens of seconds to a few minutes) generate very high accuracy orbits using either of the two observing modes described above. In this way J-MAPS can serve as a pathfinder mission, opening the field of Real-Time Space Situational Awareness (RT-SSA).

3.2 J-MAPS Autonomous Ranging Measurements

By their very nature, GEO satellite positions are essentially fixed with respect to a particular ground station. In order to calculate range to a GEO, multiple ground stations are needed in order to establish parallax, or plane-of-sky data must be fused with data from a ranging sensor such as radar.

J-MAPS will be able to make *autonomous ranging measurements*. Because J-MAPS will be moving in its own LEO orbit at approximately 7 km/sec, its orbital motion is effectively the base of the parallactic triangle. One second observations have ~ 7 km baselines while observations separated by ten seconds will have ~ 70 km baselines. Assuming the sort of measurement accuracy described in the previous section, we estimate ranging accuracy of a few kilometers or better over the course of ten of seconds of observations, with longer intervals of minutes to tens of minutes between exposures reducing the range accuracy to a few hundred meters or better.

This type of measurement is not possible from the ground, and not possible at the J-MAPS levels of accuracy with current or future systems, ground- or space-based. This is important as it deconstrains the orbital solution problem from an assumption that the RSO is in a specific orbit by allowing direct measurement of the third spatial dimension using a single observer.

3.3 J-MAPS Transition to an Operational SSA/SSN Sensor

J-MAPS is not optimized for SSA applications. If successful, however, it could serve as a pathfinder for microsatellites that are dedicated to and optimized for high metric accuracy measurements of GEO satellites in support of SSA needs. Two satellites, deployed one-half an orbit apart (as shown in Figure 9) would have an observing baseline of over 12,000 km. Simultaneous or near simultaneous observations of a specific GEO satellite would result in plane-of-sky accuracies of a few meters and ranging accuracies of a few tens of meters or better.

One could envision such a system playing a key role along with ground sensors, e.g., SST, or space-based sensors, e.g., SBSS, as part of an overall SSA architecture. A typical scenario might unfold as follows: SBSS, while scanning the GEO belt, detects a new GEO object. Initial position and velocity measurements are returned to the ground, and a high metric accuracy position measurement task is sent to two J-MAPS-derived SSA microsats. The two J-MAPS satellites take measurements and return high-accuracy positional data as described above (radial accuracy ~ tens of meters, transverse accuracy ~ meters), allowing calculation of a high accuracy orbit, or information to enable a space threat analysis, within minutes.

Because the measurements are made with satellites instead of ground stations, at least one satellite always has access to any point on the GEO belt. There are no issues regarding weather or time of day. Furthermore, in the notional orbit shown in Figure 9, both satellites would have constant access to the opposition point, the best “hunting ground” for GEO satellites because of the favorable lighting conditions. Multiple J-MAPS-class microsatellites could even be tasked to continuously monitor a “keep out” region around a high value satellites, providing a “remote defensive counterspace” capability. This capability would provide near-real time SSA, enabling rapid Space Threat Analysis and hostile manuever detection. Using this information, blue operators would be able to take defensive actions much earlier than they are currently able, significantly increasing the survivability of our highest value assets.

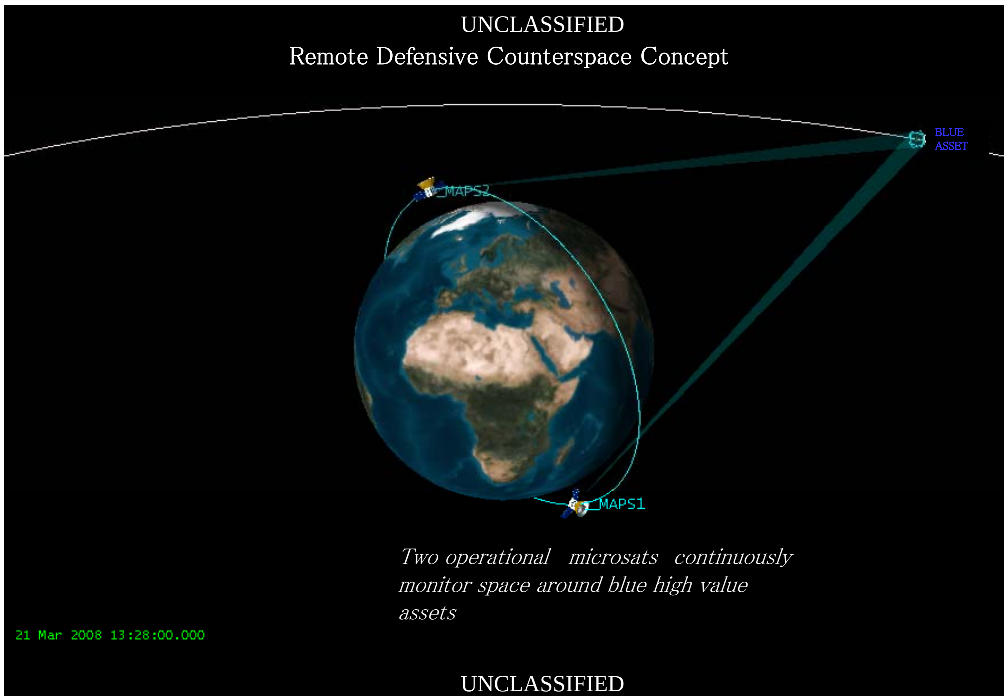


Figure 9. Two operational J-MAPS like microsatellites could continuously monitor “keep-out zones” around high value assets.

4.0 SUMMARY

The USNO is developing the space-based J-MAPS mission to support current and future star catalog and star tracker requirements. J-MAPS, a microsatellite designed to take very high precision measurements of star positions (astrometry), is also ideally suited to make high metric accuracy measurements for brighter GEO RSOs. An SSA architecture would potentially benefit from supplementing existing and planned detection assets with a dedicated high-accuracy orbit determination system or systems, with the potential for 24/7 taskability and near-real time capability. By optimizing an instrument to perform position measurement rather than detection, significant (i.e., one or more orders of magnitude) improvement may be realized in position and velocity measurement (thus, orbit determination) vs. other current and envisioned systems.

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